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Initial Development of Ice Crystal Ice Accretion at Conditions Related to Turbofan Operation at High Altitude

A thesis submitted by

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in fulfilment of the requirements of

Doctor of Philosophy

2013

Abstract

Ice accretion on external surfaces of aircraft is a widely recognised problem, but more recently identified problem of ice crystal ice accretion within aero-engine compressors during flight through deep convection systems also represents a significant hazard and forms the motivation for the present work. The experimental studies targeting solid phase ice accretion are very limited due to the high wind tunnel facilities operational cost and safety concern for in-flight icing testing, which requires flight through severe weather conditions.

In this study, a small wind tunnel was established to simulate some of the conditions relevant to aircraft engine icing from ice crystals and explore the application of a model for the initiation of ice accretion. In this facility, liquid nitrogen was used to freeze liquid water droplets generated using an ultrasonic nozzle. The liquid nitrogen section reduces the droplet temperature to less than $-40\,^{\circ}\mathrm{C}$ and maintains this temperature for sufficient time to ensure complete freezing occurs. The particle diameters were controlled by the air and water pressure delivered to the ultrasonic nozzle and particle diameters around $50\,\mu\mathrm{m}$ were generated. The ice water content was also measured experimentally and it was found to be around $0.42\,\mathrm{g/m^3}$. A temperature controller was developed to keep the specimen surface temperature essentially constant and four specimen surface temperatures were tested: -9, -5, 0, and $5\,^{\circ}\mathrm{C}$.

The wind tunnel duct had a diameter of 70 mm and was operated at the relatively low flow speed of 6.5 m/s. A cylinder with diameter of 10 mm and flat plate surface with length of 3.6 cm and a leading edge diameter of 3 mm were used as the test specimens. A microscope video camera was used to visualise a small area on the specimen surface of

9×9 mm and record the initiation of the accretion process. The experimental data were analysed using image processing techniques, and different locations around the centre line of the test specimens in the vicinity of the stagnation point were investigated. Two regions with different roughness were used on both specimens with an average roughness (R_a) for the smooth side of $0.5\,\mu$m and $1.0\,\mu$m for the rough side, but no effect of the surface roughness was observed in the experimental accretion results for these conditions.

The mathematical model for accretion initiation which was developed considers the aerodynamic, adhesive, and friction force affecting the particles in contact with the surface. The model indicates that ice accretion can occur at subfreezing conditions in the stagnation region and this effect was observed in the present experiments. The model also indicates that accretion is less likely to occur as the temperature increases due to reductions in the coefficient of friction. Such an effect was also observed in the experiments: accretion occurred most rapidly in the $-9\,^{\circ}$C case but virtually no accretion was registered in the $0\,^{\circ}$C and $5\,^{\circ}$C cases.

Although the mathematical model suggested the accretion could also initiate on a flat plate with a laminar boundary layer, this was not observed experimentally. The lack of the accretion in the laminar boundary layer configuration is attributed to the finite leading edge diameter on which substantial ice accretion was observed. The rate of accretion development on the leading edge of the flat plate was comparable to that on the large diameter cylinder specimen which is not consistent with the trends suggested by the mathematical model.

The new wind tunnel duct conditions can be controlled and solid ice particles of a uniform shape and known size distribution can be produced. The development of the new facility and the force-balance model has established useful tools which can be further enhanced in future ice accretion studies.

Associated Publications

The following publications were produced during the period of candidature:

Saleh, Khalid H. and Buttsworth, David R. and Yusaf, Talal , "Development of a small icing wind tunnel for simulating the initial stages of solid phase ice accretion", *17th Australasian Fluid Mechanics Conference*, 5-9 Dec 2010, Auckland, New Zealand.

Buttsworth, DR, Saleh, KH & Yusaf, T, "Discrete particle simulation for the initial stages of ice accretion in aircraft engines: initial model development", *3rd International Conference on Energy and Environment (ICEE)*, 7-8 December 2009, Malacca, Malaysia.

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.
I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature of Candidate

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ENDORSEMENT

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Acknowledgments

First and foremost I would like to extend my sincere appreciation and gratitude to my supervisor Prof. David Buttsworth for his support and guidance throughout my Ph.D. study. I am also grateful to him for giving me the opportunity to work on this research project which has helped me to broaden my knowledge and develop new skills.

I acknowledge the contribution of technical staff of the University of Southern Queensland for their contributions to the work resulting in this thesis. I would like to thank FoES Associated Dean (Research) A/Prof. Armando Apan and his assistant Mrs Juanita Ryan for their support. Also my deep appreciation goes to Ms Angela Windsor and Mrs Kelly Baron for helping me through my language course and for proof reading of this thesis.

I would like also to thank all of my friends and the Iraqi students at USQ especially Ahmed Al-Sabawy for his encouragement and thoughtful opinion in my personal and study issues.

Finally, I am very grateful to my father and my mother for all their efforts to raise me. Thanks to my wife for taking care of me and my son Anas through my study.

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2013

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Notation

A_s	Water droplet surface area in mm^2
A_T	Particle cross sectional area in mm^2
C	Specific heat of water in J/kg.K
C_D	Drag coefficient
D	Leading edge diameter in mm
D_{force}	Drag force in N
d_{par}	Ice particle diameter in μm
d_w	Water droplet diameter in μm
F_{ad}	Adhesion force in N
g	Gravitational acceleration in m/s^2
Gr_d	Grashof number
h_c	Convection heat transfer coefficient in $W/m^2.K$
H	Shortest distance between ice particle and the surface in μm
k	Air thermal conductivity in W/m.K
Nu_d	Nusselt number
R_a	Centre line average value in μm
Re	Reynolds number
R_z	Average peak to valley height in μm
t	Time in s
T	Temperature in °C
T_s	Air and water mixture temperature in °C
T_∞	Cold stream temperature in °C
u_e	Air speed external to the boundary layer in m/s
u_p	Ice particle speed in m/s

$\bar{u}$	Air speed in the boundary layer in m/s
U_∞	Free stream flow velocity in m/s
V	Water droplet volume in m^3
V_L	Liquid bridge volume in m^3
β	Air coefficient of thermal expansion in K^{-1}
γ	Dimensionless boundary layer thickness
δ	Boundary layer thickness in μm
ϵ	Embracing angle
η	Collection efficiency
μ	Friction coefficient
ν	Kinematic viscosity in m^2/s
ρ	Density in kg/m^3
σ	Surface tension coefficient in N/m
ϕ	Contact angle

Acronyms & Abbreviations

AERTS	Adverse Environment Rotor Test Stand
AIWT	Altitude Icing Wind Tunnel
BRAIT	Boeing Research Aerodynamic Icing Tunnel
CIRA	Italian Aerospace Research Centre
C-MAPSS40K	Commercial Modular Aero-Propulsion System Simulation 40K
FAA	Federal Aviation Administration
FENSAP-ICE	Finite Element Navier-Stokes Analysis Package
FSSP	Forward Scattering Spectrometer Probe
GRC	Glenn Research Centre
HSV	Hue Saturation Value
IRT	Icing Research Tunnel
IWC	Ice Water Content
JKR	Johnson, Kendal and Robert
LIRL	LeClerc Icing Research Laboratory
LWC	Liquid Water Content
NRC	National Research Council
RANS	Reynolds Averaged Navier-Stokes
RATFac	Research Altitude Test Facility
RGB	Red Green Blue
SLD	Supercooled Large Droplet
SLW	Supercooled Liquid Water content
TWC	Total Water Content
UHV	Ultra High Vacuum